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Sedimentological analysis and log-sequence stratigraphy of X-Field, Niger Delta

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Abstract

Sedimentological analyses were carried out on one-hundred and fifteen (115) ditch-cutting samples of depth ranges (6240ft-10020ft) from well-X, in the Central Swamp Depobelt, of the Niger Delta Basin to determine the depositional environment of the sediments. The ditch-cutting samples were analysed using a stereo microscope for the lithologic description, thirty-three (33) samples were identified as sandstone, while the other eighty-two (82) samples were classified as shale. Grain size analysis was carried out using a set of sieves on the thirty-three (33) samples identified as sandstone. The grain size analysis results were visualised in a graphical method from which some simple statistical parameters were derived. The sample description yielded lithologies that are sandstone and shale. The sandstones were found to be fine to medium-grained, poorly sorted to moderately well sorted. They were fine to coarsely skewed with kurtosis values indicating the sandstones were mostly Leptokurtic. The shales were light to dark grey shales controlled by organic content in the shale. This finally produced a lithologic framework of the well. Bivariate plots of the relationships between the graphic statistical moments (mean, median, standard deviation, skewness and kurtosis) revealed that sediments were deposited in a fluvial environment with the samples falling with the river processes with minor to negligible influence from wave and beach processes. Log-sequence stratigraphic analyses of wireline logs revealed five (5) depositional sequences each beginning and ending with a sequence boundary and also containing lowstand, highstand and transgressive parasequences.

Keywords: Sedimentology; Grain size analysis; Palaeo-depositional environment; Sequence stratigraphy

1. Introduction

Sedimentary rocks provide records of the Earth's past, including the conditions of the paleodepositional environment in which they were formed [4]. Understanding the paleodepositional environment is crucial for interpreting the depositional history of sedimentary basins, reconstructing ancient landscapes, and predicting reservoir quality for hydrocarbon exploration.

Reconstruction of depositional systems of sediments is of crucial importance since it establishes a foundation for predicting reservoir facies and identifying potential petroleum sources and seal facies [30]. Paleodepositional environments can be broadly classified as continental, marine, and transitional [4]. The sedimentary rocks formed in these environments exhibit distinctive characteristics, such as sediment composition, grain size distribution, sedimentary structures, and fossil content. By analysing these characteristics, sedimentologists can recreate ancient depositional environments and deduce the geological history of the area.

In recent years, sedimentology and paleodepositional environment studies have been growing in significance within the oil and gas sector. Several studies on the palynology, sedimentology, paleodepositional environment and sequence stratigraphy etc., on the Niger Delta, studies have been undertaken to expand the existing knowledge base of the geology and history of the Delta [32].

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This study aims to investigate the sedimentology and paleodepositional environment of a selected well in the Niger Delta basin, with a focus on understanding the depositional history. The study will analyse the drill cuttings in the laboratory and will provide our understanding of the depositional setting of the target area, offering valuable insights into the geologic processes that occurred in the past. The study also involves the use of wireline logs in reconstructing the depositional cycles that have occurred in the studied area based on their gamma-ray log response.

1.1. The Study Area

The study area is situated within the Central Swamp Depobelt, adjacent to the Greater Ughelli Depobelt, which dates back to the Oligocene, located in the onshore region of the Niger Delta sedimentary basin (Figure 1). It is bounded by the geographical coordinates of latitudes 4°N to 5°N and longitudes 6° E and 7° E.

Figure 1 Geologic map of the Niger Delta showing depobelts and structure. The location of the well is indicated with the red star [9]

1.2. Regional Geology of The Niger Delta Basin

The Niger Delta Basin, located in the Niger Delta and Gulf of Guinea on Nigeria's western coast [38], is a clastic-filled, extensional rift basin formed due to the split between the South American and African plates. It spans over 75,000 km^2 sub-aerially and extends more than 300,000 km^2 from apex to mouth [11, 38]. Rifting began in the late Jurassic and ceased by the mid-Cretaceous, followed by a coastal transgression during the Paleocene, leading to the formation of the Akata, Agbada, and Benin Formations [11, 34].

Lithologically, the Cretaceous section of the Niger Delta Basin is inferred from adjacent regions like the Anambra Basin [38]. The Late Cretaceous and Paleocene periods saw the deposition of shales such as the Asu River, Eze-Uku, and Nkporo shales [27, 33]. The Paleocene Sokoto transgression led to the deposition of the Akata shale, which transitioned into wave-dominated sedimentation in the Eocene [5].

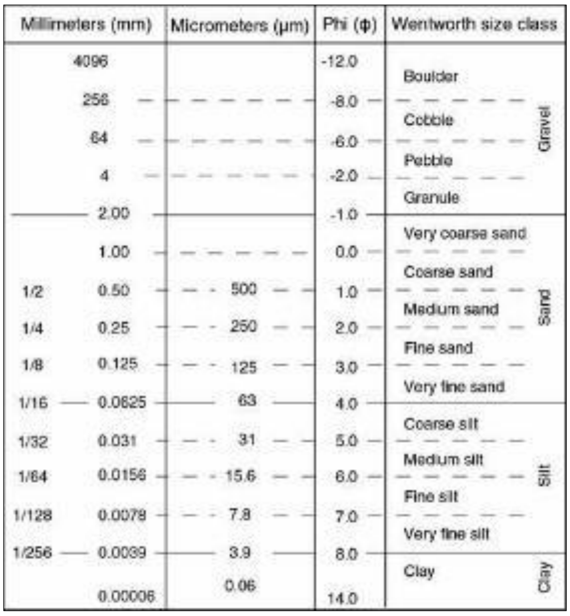
Stratigraphically, the Niger Delta is characterized by the Akata, Agbada, and Benin Formations [34]. The Akata Formation consists of marine shales with sand streaks, reaching thicknesses of up to 20,000 m in some areas [9, 43]. The Agbada Formation, lying above Akata, consists of alternating sand and shale layers, with thicknesses exceeding 3500 m, forming the primary petroleum-bearing unit [8]. The Benin Formation, composed predominantly of sands, is the topmost unit, extending across the entire basin and dating from the Oligocene to the present [2, 28].

1.3. Grain Size Analysis

Grain size analysis is a fundamental tool in sedimentology used to assess the distribution of sediment particles within a sample. This analysis helps determine the transport history, energy conditions, and origin of sediments.

Sediment size is a fundamental characteristic and is typically categorized into gravel, sand, and mud. While the concept of grain size is simple, accurately measuring particles poses challenges [42, 22]. The Wentworth grade scale (figure 2) [43] is widely used for this classification and is often modified using Krumbein's phi (ϕ) scale [21], which applies a logarithmic transformation to grade boundaries while retaining the original grade names.

Larger particles like boulders and gravel are measured manually, while sand is typically sieved. For finer sediments like silt and clay, texture can be used for differentiation, though more advanced techniques, such as thin-section microscope analysis and electron microscopy, are required for precise measurements in well-cemented sediments [24].



Millimeters (mm)		Micrometers (μm)	Phi (ϕ)	Wentworth size class	
	4096		-12.0	Boulder	Gravel
	256		-8.0	Cobble	
	64		-6.0	Pebble	
	4		-2.0	Granule	
	2.00		-1.0	Very coarse sand	Sand
	1.00		0.0	Coarse sand	
1/2	0.50	500	1.0	Medium sand	
1/4	0.25	250	2.0	Fine sand	
1/8	0.125	125	3.0	Very fine sand	
1/16	0.0625	63	4.0	Coarse silt	Silt
1/32	0.031	31	5.0	Medium silt	
1/64	0.0156	15.6	6.0	Fine silt	
1/128	0.0078	7.8	7.0	Very fine silt	
1/256	0.0039	3.9	8.0	Clay	Clay
	0.00006	0.06	14.0		

Figure 2 Grain size classification using the Wentworth scale [43, 15]

Statistical parameters, such as central tendency (median, mode, mean), sorting, skewness, and kurtosis, help describe the distribution and characteristics of the grains [36]. The Graphic Mean is the ideal graphic measure for measuring the overall size of sediments [12], while sorting, expressed as Graphic Standard Deviation, indicates the uniformity of grain sizes. Skewness shows the asymmetry in the size distribution, with positive skewness indicating a coarse bias and negative skewness a fine bias. Kurtosis, describing the "peakedness" of the grain size curve, can be leptokurtic (more peaked), platykurtic (flatter), or mesokurtic (normal) [37].

These statistical methods, initially defined by Trask [37] and refined by Folk and Ward [13], are essential for granulometric analyses.

Tables 1, 2, and 3 outline the granulometry statistical parameters used in these analyses. Accurate grain size data are crucial for interpreting how sand texture relates to reservoir characteristics.

Table 1 Sediment sorting interpretation from Standard Deviation [13]

Values from	**To**	**Sorting**
0.00	0.35	very well sorted
0.35	0.50	well sorted
0.50	0.71	moderately well sorted
0.71	1.00	moderately sorted
1.00	2.00	poorly sorted
2.00	4.00	very poorly sorted
>4.00		extremely poorly sorted

Table 2 Sediment interpretation of Graphical Skewness [13]

From	To	Mathematically:	Graphical Skewness
+1.00	+0.30	Strongly positive skewed	Very Fine Skewed
+0.30	+0.10	Positive skewed	Fine Skewed
+0.10	-0.10	Near symmetrical	Symmetrical
- 0.10	0.30	Negative skewed	Coarse Skewed
-0.30	- 1.00	Strongly negative skewed	Very Coarse Skewed

Table 3 Sediment interpretation of Kurtosis [13]

From	To	Peakiness
0.41	0.67	very platykurtic
0.67	0.90	Platykurtic
0.90	1.10	Mesokurtic
1.10	1.50	Leptokurtic
1.50	3.00	very leptokurtic
>3.00		Extremely leptokurtic

Significant research has been dedicated to linking sediment particle size distribution with depositional environments. Stewart [35] suggested that plotting skewness versus median diameter, or median diameter versus standard deviation, helps differentiate between river and wave processes. Similarly, Mason and Folk [23] recommended plotting graphic skewness against graphic kurtosis to distinguish between aeolian flats, beaches, and dunes. Friedman [14] proposed a bivariate plot of skewness against standard deviation to separate sands deposited in beach and river environments. Moiola and Weiser [26] expanded these comparisons by utilizing Folk and Ward's textural characteristics—skewness versus mean and standard deviation versus mean—to distinguish between sands from beaches, aeolian dunes, and rivers.

1.4. Log-Sequence Stratigraphy

Sequence stratigraphy is the study of rock relationships within a chronostratigraphic framework, focusing on repetitive, genetically related strata bounded by surfaces of erosion or deposition [25, 7]. Unlike lithostratigraphy, which emphasizes compositional similarities, sequence stratigraphy maps strata based on time-related surfaces like maximum flooding surfaces and subaerial unconformities [40]. This approach helps understand Earth's surface evolution over time.

The method links sequence boundaries and stratigraphic units to changes in relative sea level, influenced by global eustatic sea level and regional subsidence (tectonic, thermal, and load-induced). These vertical forces, combined with sediment supply rates, control the accumulation of sediment in a basin. Parasequences, upward-shallowing successions of facies bounded by flooded surfaces, differ from sequences in their bounding surfaces rather than size. Both sequences and parasequences may exhibit consistent trends in thickness and facies composition, forming stacking patterns—retrogradational, aggradational, progradational, and degradational [40].

Parasequence sets often lead to log patterns, where upward increases in gamma-ray values suggest fining-upward fluvial channel deposits and coarsening-upward trends indicate deltaic progradation. Other log motifs, like cylindrical patterns, reflect braided channels or tidal deposits, while serrated motifs point to intercalated shales and sandstones from various depositional processes [29, 19].

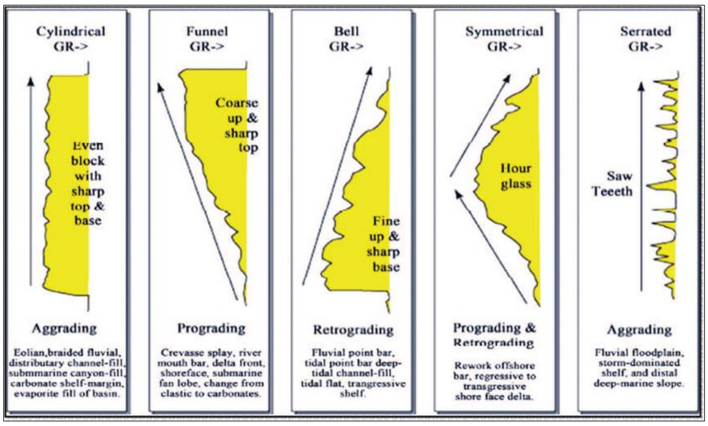


Figure 3 Well-log response character for different environments [3]

1.5. Review of previous study

Previous studies have provided valuable insights into sedimentological conditions and sequence stratigraphy. Osokpor & Maju-Oyovwikowhe [30] examined the paleodepositional environment and developed a sequence-stratigraphic framework for the TN-1 well in the Niger Delta Basin. By integrating litho- and biofacies data, they identified five paleodepositional cycles, ranging from the distal delta plain to bathyal environments. Their study highlighted the importance of integrated approaches for sequence stratigraphy in exploration and exploitation. Kairyte & Stevens [18] applied two techniques to analyse grain size trends and sediment transport in the coastal zone of Lithuania. They used "grain size trend analysis" and another interpretive technique to assess sediment erosion and accumulation. Their findings showed wave-induced sediment transport perpendicular to the coast in shallow areas, with coast-parallel transport dominating the study region. Erosion was found in deeper offshore areas, while accumulation occurred in the central zone. Osokpor & Okiti [31] focused on outcropping sediments in the Lower Middle Niger Basin. Their study of the Lokoja Formation defined several lithofacies, indicating a continental fluvial paleodepositional environment with a progradational architecture formed during sea-level fall. Ahmad et al. [1] studied the Fort Member of the Jurassic Jaisalmer Formation. Granulometric analysis of sandstone samples revealed high-energy, beach-like depositional environments. Their findings suggested a broad marine environment, from the inner shelf to the upper shoreface, based on textural metrics like skewness and standard deviation.

2. Materials and methods

2.1. Grain size analysis

This study focused on the composition and depositional conditions of sedimentary rocks through the analysis of well samples from Well X in the Niger Delta. The samples were obtained from depths ranging from 6,240 ft to 10,020 ft at 30 ft intervals, with grain size analysis performed on thirty-three sandstone samples collected from ditch cuttings. Well-log data, covering intervals from 1,747 ft to 2,831 ft, were also used for sequence stratigraphy.

The samples were sun-dried at a temperature of about 30°C and then disaggregated in the laboratory using a mortar and rubber-padded pestle to ensure they were not cluttered. Approximately 25 g of each sample was placed into petri dishes for further analysis. Eight mesh sizes of sieves, arranged in descending order, were used to separate the samples based on their grain sizes. To prevent the loss of fine particles, the grains were given time to settle before measurements were taken. The weight of the grains retained in each sieve was recorded in a distribution table. Cumulative frequency distribution curves were plotted based on the weighted fractions, and key statistical parameters, including the median, mode, and mean, were calculated to assess sediment sorting.

Additional statistical parameters were also derived to aid in the interpretation of the depositional environment. The following formulae were used for the calculation of the Graphic Mean, Graphic Standard Deviation, Graphic Skewness and Graphic Kurtosis, and the interpretations were made based on Folk and Ward's classification scheme [13].

$$\text{Graphic Mean} M_{\tau} = \frac{\phi_{16}+\phi_{50}+\phi_{84}}{3},$$

$$\text{Graphic Standard Deviation} \sigma_{i} = \frac{\phi_{84}-\phi_{16}}{4} + \frac{\phi_{95}-\phi_{5}}{6.6}$$

$$\text{Graphic Skewness} SK_i = \frac{(\phi_{84}+\phi_{16}-2\phi_{50})}{2(\phi_{84}-\phi_{16})} + \frac{(\phi_{95}+\phi_{5}-2\phi_{50})}{2(\phi_{95}-\phi_{5})}$$

$$\text{Graphic Kurtosis} K_G = \frac{(\phi_{95}-\phi_{25})}{2.44(\phi_{95}-\phi_{25})}$$

2.2. Sequence Stratigraphic Analysis

The study utilized well-log data suites, including Gamma Ray (GR) Logs, Spontaneous Potential (SP) Logs, Porosity Logs, and Resistivity Logs. These logs were crucial for identifying lithofacies and depositional environments within the well field. The Gamma Ray Log, in particular, was instrumental in determining lithofacies and depositional environments by highlighting fining and coarsening upward signatures. The logs were displayed at consistent scales to better visualize log trends and recognize facies stacking patterns, parasequences, and sequence stratigraphic surfaces, including sequence boundaries (SB) and maximum flooding surfaces (MFS).

The Maximum Flooding Surface (MFS) was identified on wireline logs as the boundary between retrogradational and progradational parasequence sets, characterized by maximum shale peaks and well-developed shales on the GR log. The Transgressive Surface (TS), marking the beginning of a period when accommodation space creation exceeds sediment supply, was associated with the base of retrogradational parasequence stacking patterns in the transgressive systems tract. Sequence boundaries (SB), significant erosional unconformities formed by falling sea levels, were identified as capping the previous highstand systems tract and eroding underlying sediments deposited during forced regressions [6]. The study also recognized and mapped various systems tracts—Lowstand Systems Tract, Transgressive Systems Tract, and Highstand Systems Tract—using the depositional sequence model [39, 40].

3. Results

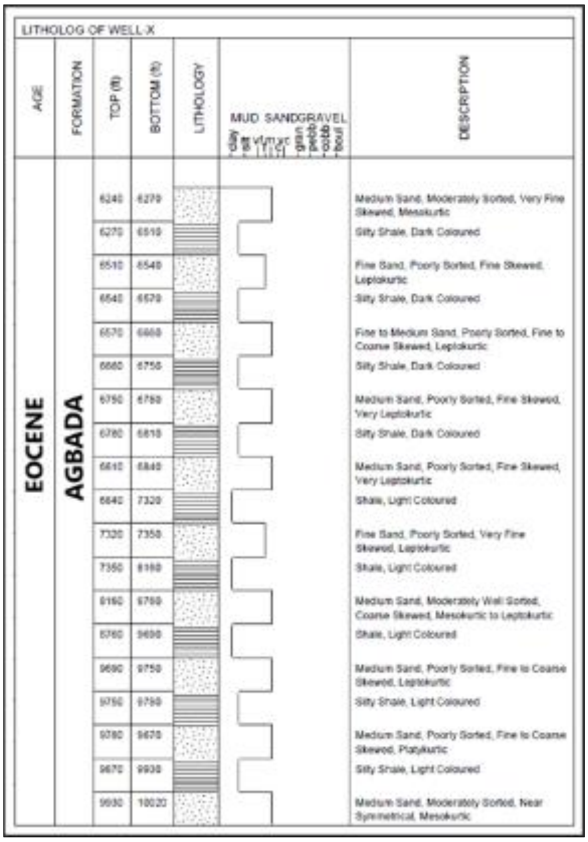


Figure 4 Lithologic log of the well section with summary lithologic description, facies, depth range of lithostratigraphic units in Well-X

Figure 4 shows the litholog of the samples from Well-X, the samples are obtained from the Agbada formation which was deposited in the Eocene age. The sample interpretations were made based on Folk and Ward's classification scheme [13].

Table 4 shows a description of the lithofacies and sub-lithofacies that were identified from the megascopic analysis of ditch-cuttings. Two major lithofacies were identified namely Sandstone and Shale. with sorting varying between moderately well-sorted to poorly sorted. The shale facies were either silty or sandy, colour varied from light grey to dark grey.

Table 4 The various lithofacies identified in the studied well

Lithofacies	**Sub-facies**	**Description**
Sandstone facies	Fine-grained Sandstone	Fine to medium-grained, fine to coarse skewed, moderately well sorted to poorly sort.
	Medium-grained Sandstone	Fine to medium-grained, fine to coarse skewed, moderately well sorted to poorly sort.
Shale facies	Silty shale	Light grey to dark fissile carbonaceous shales, the shale that appears dark at the bottom indicates the presence of organic matter.
	Sandy shale	

Histogram plots were used to visualize the distribution of statistical metrics for Well-X samples. Figure 5 shows that the graphic mean values ranged from 1.5φ to 2.6φ, indicating that most samples were classified as medium-grained sandstone (22 samples) or fine-grained sandstone (11 samples). Figure 6 reveals that sorting values ranged from 0.5 to 2, with five samples being moderately well sorted, eight moderately sorted, and twenty poorly sorted. Figure 7 displays graphic skewness values between -0.4 and 0.4; fourteen samples were classified as coarse skewed, nine as near symmetrical, and eight as fine skewed. Lastly, Figure 8 shows graphic kurtosis values from 0.75 to 1.8, with four samples classified as platykurtic, nine as mesokurtic, and twenty as leptokurtic.

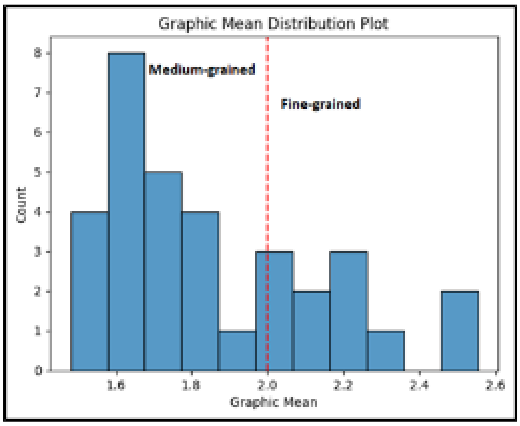


Figure 5 Graphic mean distribution plot

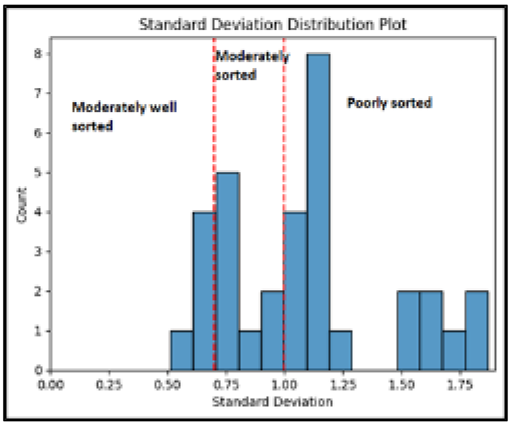


Figure 6 Graphic Standard deviation distribution plot

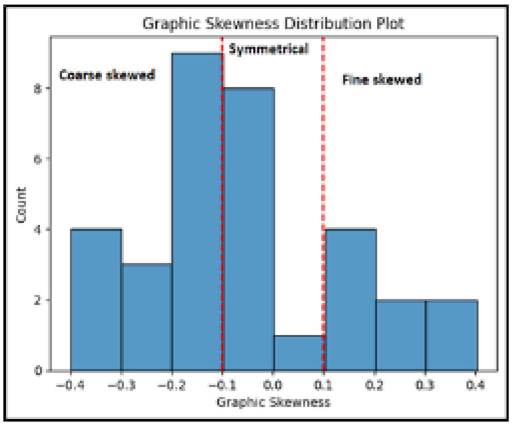


Figure 7 Graphic skewness distribution plot

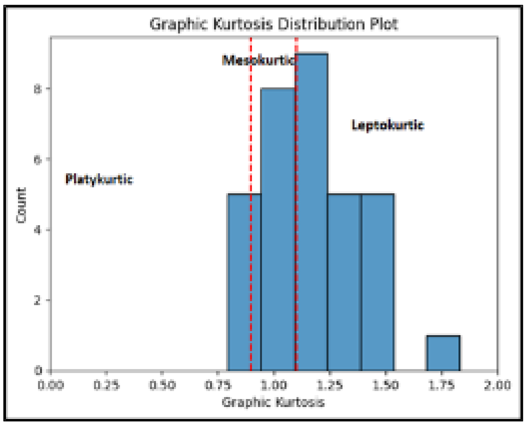


Figure 8 Graphic kurtosis distribution plot

The mean size distribution pattern indicates fluctuations in the depositional environment with fine-to-medium-grained sands deposited in a high-energy environment. The poor to moderately well-sorted grain is indicative of the deposition of sand during the little sorting in the fluvial regime [31]. The positive to negative skewness character of the sands indicates deposition in a moderate energy condition. Most of the kurtosis values are leptokurtic indicating that the central portion of the distribution was poorly sorted similarly to the extreme values. Large populations of sub-angular, angular and subrounded grains indicate short transportation of sediments.

Figure 9 Is a bivariate plot of the inclusive graphic standard deviation versus the median diameter of the Well-X samples. The scatter plot after Stewart [35] and Moiola & Wieser [26] distinguishes between river, aeolian dune and beach sandstones. From the plot, it was revealed that the sandstones fall within the river-process sandstone field. It may be concluded that these sediments probably must have been deposited in a high-energy environment where fluvial processes are dominant.

Figure 10 Is a scatter plot between the two size parameters, graphic mean size and inclusive graphic skewness [14, 26], which distinguishes between river processes and wave processes. The plot indicates a fluvial environment of deposition as most of the plotted sandstone samples were concentrated in the river field, with a minor wave influence

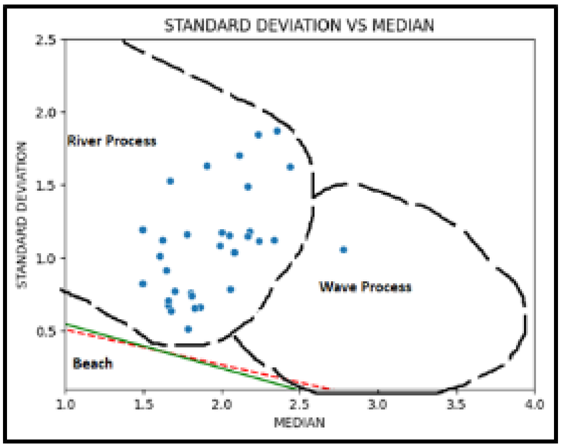


Figure 9 Bivariate plot of inclusive graphic standard deviation versus median diameter after Stewart [35] and Moiola & Wieser [26]. Circles correspond to Well-X sandstones

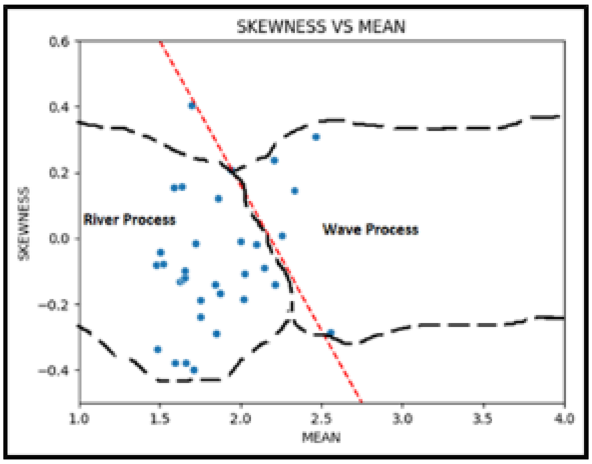


Figure 10 Bivariate plot of inclusive graphic skewness versus graphic mean diameter after Friedman [14] and Moiola & Wieser [26]. Circles correspond to Well-X sandstones

Similarly, the scatter plot (Figure 11) between the size parameters of inclusive graphic skewness and graphic kurtosis [23, 26], also suggests a fluvial environment with a minor wave influence.

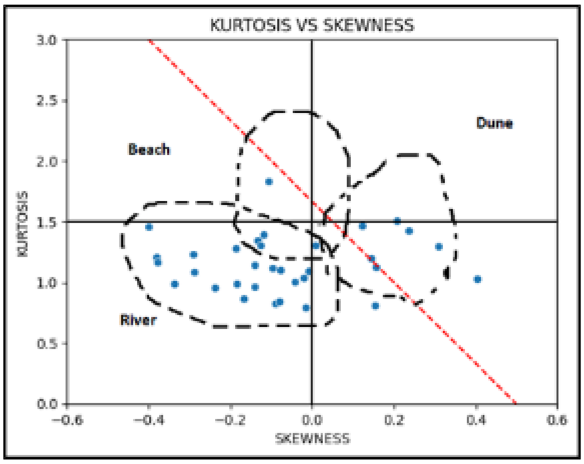


Figure 11 Bivariate plot of inclusive graphic kurtosis versus graphic skewness after Mason and Folk [23] and Moiola &Wieser [26]. Circles correspond to Well-X sandstones

Figure 12 shows the scatter plot of the graphic mean size versus inclusive graphic standard deviation (sorting) has a positive relationship between size and sorting which indicates a decrease in grain size with increased sorting which reflects fluctuating hydrodynamic conditions during deposition. The plot distinguishes between river sands and beach or coastal dunes [14, 26]. The plots suggest a fluvial environment as the samples fall in a river-dominated field.

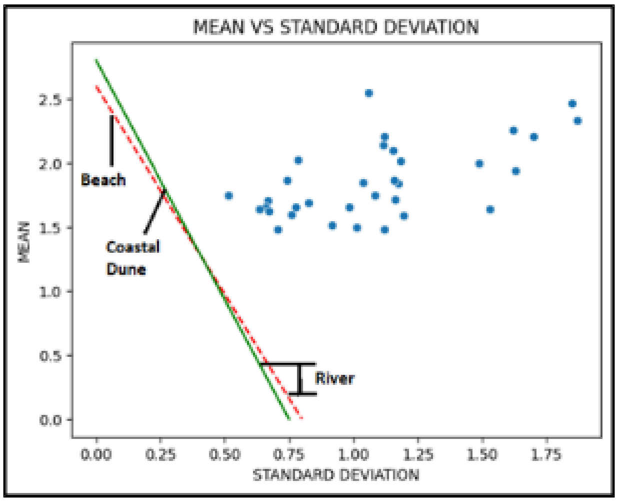


Figure 12 Bivariate plot of mean size versus inclusive graphic standard deviation after Friedman [14] and Moiola & Wieser [26]. Circles correspond to Well-X sandstones.

The bivariate plot depicted in Figure 13 is a scatter plot of graphic skewness against the graphic standard deviation used to distinguish between river sands and beach sands. The results were similar to those of the previous plots, indicating that the samples were deposited in a fluvial environment, as most of the sands fell within the river field.

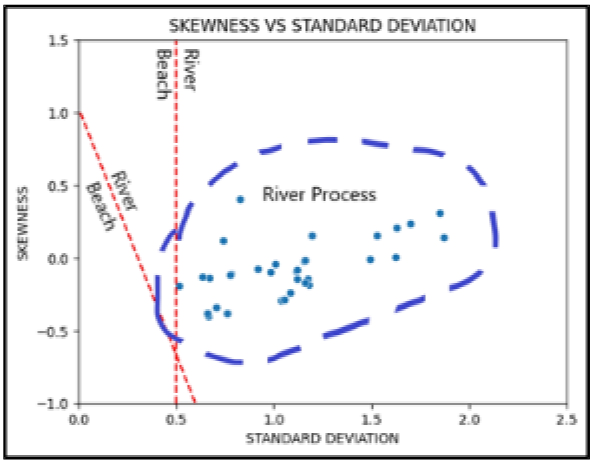


Figure 13 Bivariate plot of mean size versus inclusive graphic standard deviation after Friedman [14] and Moiola & Wieser [26]. Circles correspond to Well-X sandstones

Stratigraphic analysis based on the sequence for Well-X was used as a control to establish the key stratigraphic surfaces (Figure 14). Five major depositional sequences (DS) were mapped and delineated across the well and are located within the paralic Agbada Formation of the Niger Delta Basin. These sequences are defined by five maximum flooding surfaces (MFS) and five sequence boundaries (SB). The sequence boundaries were identified by the change from a retrogradational parasequence of shale to a progradational variation of thick sand; while the maximum flooding surface was marked by the abrupt change from a thick layer of transgressive shale to an aggradational sequence of sand. These surfaces correspond with the regional Niger Delta chronostratigraphic chart and they give rise to corresponding lowstand, transgressive and highstand systems tracts.

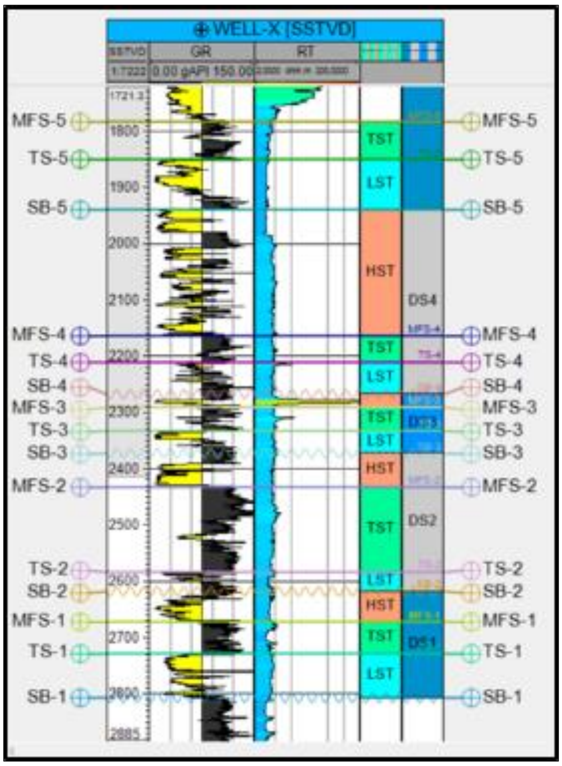


Figure 14 Representative parasequence stacking patterns and depositional sequences in Well-X

3.1. Depositional Sequences

- Depositional Sequence 1: This is the oldest of the five sequences in the study area and it is bonded at the base by the SB-1 and at the top by SB-2 respectively. The LST, TST and HST have similar thickness indicating a steady rise and fall of the sea level during this depositional cycle.
- Depositional Sequence 2: This depositional sequence directly overlies the depositional sequence 1, and it is bounded by SB-2 at the base and SB-3 at the top. In this cycle, the LST has a short span while the TST has a long span, this indicates that there was a rapid increase in sea level during this depositional sequence leading to formation of thick shale beds.
- Depositional Sequence 3: This depositional sequence directly overlies the depositional sequence 2, and it is bounded by SB-3 at the base and SB-4 at the top. In this cycle, the LST, TST and HST have short spans, this indicates that there was a rapid rise and fall of sea level during this depositional sequence leading to formation of thin beds.
- Depositional Sequence 4: This depositional sequence directly overlies the depositional sequence 3, and it is bounded by SB-4 at the base and SB-5 at the top. This cycle is similar to previous depositional cycle in terms of how long the LST and TST stages lasted. However, the HST has a longer span, with saw-teeth stacking pattern. This indicates that the sediments during the HST stage were deposited in a storm-dominated shelf.
- Depositional Sequence 5: This is the youngest of the five sequences in the study area and it is bonded at the base by the SB-5. The LST and TST have similar thickness indicating a steady rise and fall of the sea level during this depositional cycle, and the HST bounded at the bottom by the MFS-5 is still ongoing.

4. Conclusion

The sedimentological and sequence stratigraphic analyses of Well-X in the central swamp depobelts offer a thorough understanding of the Agbada Formation's depositional environment in the Niger Delta Basin. Megascopic analysis of ditch-cuttings identified alternating sandstone and shale facies, supporting a fluvial deposition interpretation. Sieve analysis of the sandstone samples confirmed this interpretation by indicating river-dominated processes. The log-sequence stratigraphic analysis of wireline logs revealed five depositional sequences, characterized by lowstand, highstand, and transgressive parasequence system tracts. Both sedimentological and stratigraphic methods proved reliable in providing a detailed and accurate interpretation of the sedimentary processes and depositional history in the region.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

I declare that there is no conflict of interest.

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